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Fundamental Research Policy for the Digital Battlefield

Leland Joe, Phillip M. Feldman

Arroyo Center

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Fundamental Research Policy for the Digital Battlefield

Leland Joe, Phillip M. Feldman

Prepared for the United States Army

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Arroyo Center

Approved for public release; distribution unlimited

PREFACE

This study examines the ability of the commercial marketplace to meet the future needs of the Army, and it identifies research areas for Army investment. The study focuses on identifying those fundamental communications network characteristics (physical topology, operating environment, user needs) that uniquely define the Army's communications problem and are not being addressed by commercially driven research. This study was sponsored by the Assistant Deputy Chief of Staff for Combat Developments, Headquarters U.S. Army Training and Doctrine Command. The research was conducted in the Force Development and Technology Program of RAND's Arroyo Center, a federally funded research and development center sponsored by the United States Army. The analysis and recommendations of this study are the sole responsibility of the authors. This study will be of interest to communications system designers and acquisition authorities.

SUMMARY

The Department of Defense is looking to commercial information technologies to meet its needs for digitization equipment. The commercial marketplace has shown responsiveness and agility in meeting the growing civilian demands for robust, reliable, and ubiquitous communications. Many of these technologies are of direct use or can be leveraged to develop systems for the military.

But although commercial systems are advancing rapidly, it is not clear that they will meet all military needs, especially those of the Army. Evolving Army warfighting concepts for Force XXI and Army After Next rely heavily on dispersed and mobile forces, connected by reliable, secure, high-speed, and high-capacity communications networks. Operational success of these concepts will depend on the pace of technology.

This study examines the ability of the commercial marketplace to meet the future needs of the Army on the tactical battlefield. A framework is developed linking the Army's future operational capabilities to system design tradeoffs. This framework is then used to examine how well commercial systems can meet Army needs. We find, using this methodology, that commercial wireless systems will not meet the Army's future needs, and the Army needs to trade off requirements with future investments in research and Army-unique systems.

These tradeoffs are complicated because:

1. Tradeoffs at one level of the design process affect the choices at other levels.
2. Tradeoffs are not necessarily driven by requirements, but also by external constraints of business practices and the external environment.

Specific recommendations for Army investment in specific technologies are provided in a companion research report by Phillip M. Feldman, *Emerging Commercial Mobile Wireless Technology and Standards: Suitable for The Army?* MR-960-A, 1998.

Fundamental Research Policy for the Digital Battlefield

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This study examines the ability of the commercial marketplace to meet the future needs of the Army, and it identifies research areas for Army investment. The study focuses on identifying the fundamental communications network characteristics (physical topology, operating environment, user needs) that uniquely define the Army''s communications problem and are not being addressed by commercially driven research.

This briefing presents the study methodology and results. A more detailed presentation is provided in Phillip M. Feldman, *Emerging Commercial Mobile Wireless Technology and Standards: Suitable for the Army?* MR-960-A, 1998.

Objectives and Scope

- What are the tradeoffs between commercial information network technologies and future Army needs?
  - What Army needs can be met by commercial technologies?
  - What additional research must be funded by the Army?
- Focus -- wireless communications technologies for the tactical battlefield
- Sponsor -- Assistant Deputy Chief of Staff for Combat Developments, TRADOC Headquarters

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Army communications systems currently being developed for the digital battlefield rely heavily on commercially derived technology However, purely commercially driven network technologies may not meet the needs of the Army, especially with evolving mobility and dispersion concepts for Force XXI and the Army After Next. Army specific needs may require additional investment to mitigate operational risk to these concepts. The objective of this project is to examine the tradeoffs between developing commercial information network technologies and future Army needs and to identify and recommend critical research areas that will need Army sponsorship.

The focus of the study is on wireless communications technologies for the tactical battlefield. The study sponsor is the Assistant Deputy Chief of Staff for Combat Developments, TRADOC Headquarters.

Outline

- Communications system design framework
- Design process
- Commercial wireless technology
- System level modeling issues
- Concluding remarks

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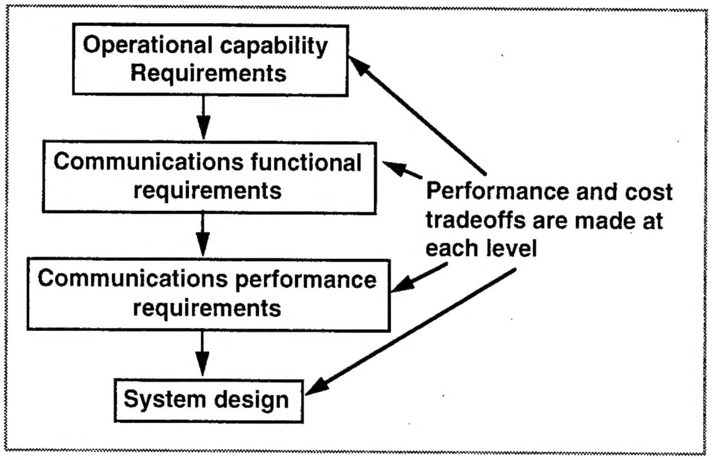
The briefing consists of the following sections:

1. Communications system design framework. This section presents an analytic framework for relating operational requirements to system design tradeoffs. Communications engineers must design systems to meet requirements while often also satisfying constraints imposed on them by existing business practices (the acquisition system) and the external environment (e.g., spectrum allocation.)
2. Design process. This section illustrates how the analytic framework can be used to determine how operational requirements, combined with external constraints, can lead to differing commercial and military system designs.
3. Commercial wireless technologies. This section discusses in detail the state of commercial wireless technologies, matching them to Army requirements.
4. System-level modeling issues. Models and simulations are one of the analytic tools used for making tradeoffs. This short section describes a major shortfall in developing a reference model at the system level. This shortfall can result in much confusion and misunderstanding about the ability of systems to meet requirements.
5. Concluding remarks.

Linking Requirements to System Design Tradeoffs



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This chart shows the description of the system design process used in this study to relate operational requirements to system design. The process is shown in four levels, each of which addresses system design in increasing detail.

The first level is definition of operational capability requirements. These are determined by the operational user and are written in operationally meaningful terms. One product at this level is the operational architecture.

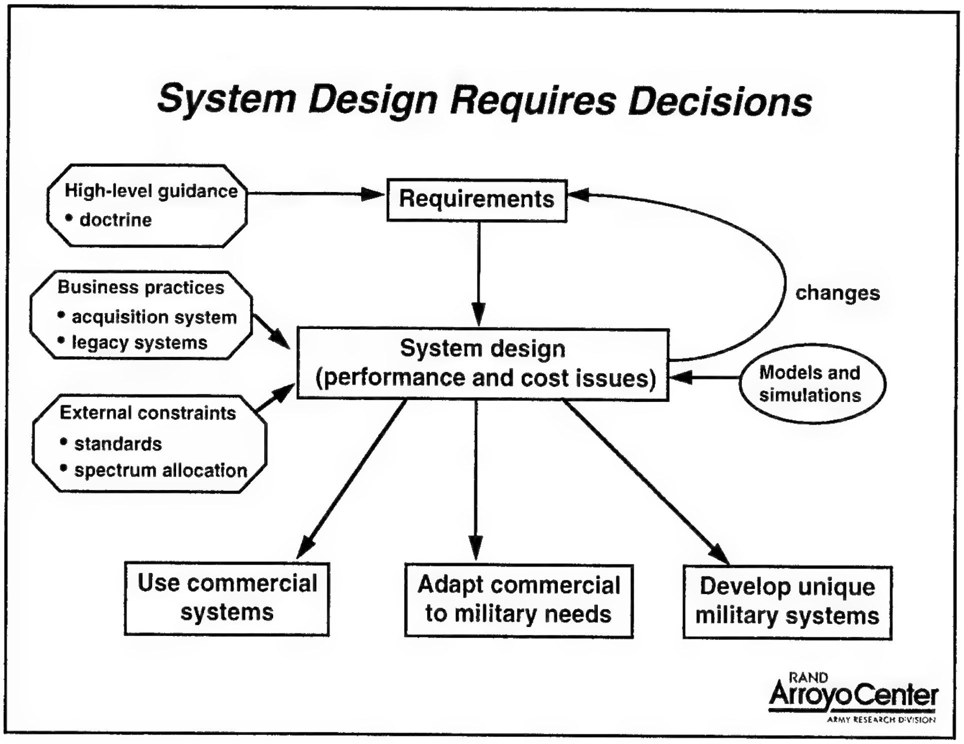
The next level is communications functional performance. At this level, communicators translate operational requirements into more specific requirements for the communications system (e.g., user and infrastructure mobility, user dispersion, etc.) .

The next level is communications system requirements. At this level, system designers develop appropriate needs at an engineering level (e.g., timeliness and throughput requirements).

The final level requires the specific system design choices (e.g., error correction choice, coding). One product at this level is the system architecture.

A more complete listing of typical categories at each level is provided in the backup section of this briefing.

It is important to recognize that each of these levels is typically performed by a different organization (users, system architects, system designers). At each level, performance and cost tradeoffs are made to balance conflicting needs. Tradeoffs affect decisions at other levels, and if the overall design process is not tightly coupled, mismatches can occur and requirements will not be met.



System design requires choices. The system design tradeoff is sometimes feasible, with the Army able to either: use commercial systems and technologies directly; adapt commercial systems to military needs; or develop unique military systems to meet needs.

The left-hand side of this chart shows some of the external factors that influence tradeoffs. At the requirements level, high-level guidance such as doctrine will determine and influence the choice of operational requirements. In the system design process, external constraints due to business practices (dynamics of the system for acquiring communications technologies, impact of legacy systems) and to the external environment (impact of commercial standards, the electromagnetic spectrum available to the military) may play as large a role in tradeoffs as the requirements that must be met (as will be shown later in the report).

Models and simulations can be used to make tradeoffs, and it is important to have a recognized reference set of models, situations, and data sets for making fair and consistent tradeoffs among competing systems and technologies.

However, the tradeoff is not always feasible, and it is possible that technology will have to be aligned, where possible, to satisfy requirements. As technology matures, unmet requirements will be addressed.

Outline

- Communications system design framework
- Design process
  - Army mobility requirements
  - Commercial satellite communications trends
- Design tradeoffs
- System level modeling issues
- Concluding remarks

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The next section provides an example of the design process, specifically addressing the operational requirement for user and infrastructure mobility. The design process framework is used to show how commercial and military system designs diverge.

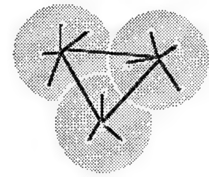
The section also discusses the ability of commercial satellite technology trends to meet Army needs.

Mobility Requires Different Physical Network Structure

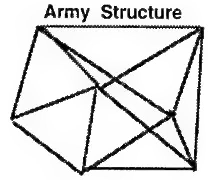
Communications functional requirements

Commercial and Army rqmts	Army unique
• access	• dispersion
• connectivity	• deployability
• user mobility	• infrastructure mobility

Commercial Structure



Army Structure



- Commercial cellular networks depend on fixed network infrastructure
  - users can move from cell to cell, but infrastructure supports high data rate and doesn't move
- Army users and backbone need to be mobile

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Both commercial and military communications systems are focused on increased mobility in the future. However, differences in requirements result in different physical network structures.

Commercial user requirements focus on increasing access to communications, improved connectivity of users (mobile-to-mobile), and user mobility. This matches many of the Army's requirements also. However, the Army has additional requirements for dispersion of users and communications infrastructure, worldwide deployability, and mobility of communications infrastructure.

These additional requirements result in a different physical structure of networks. Commercial systems focus on user mobility but an otherwise fixed infrastructure. Mobile users link to fixed ground stations, which are connected for subsequent routing either to another mobile user or to a public service telephone provider. (Note: The fixed infrastructure is usually ground based for efficiency. New commercial cellular systems may use wireless, even satellite based, routing for areas with no ground infrastructure. But these systems are still tied to a fixed ground station network.)

Army users require user and infrastructure mobility. The resulting physical structure has many nodes, each of which can be mobile, all acting both as a user interface and as a router of messages. This structure provides mobility, dispersion, and deployability. Packet-switched networks are an example of this type of structure.

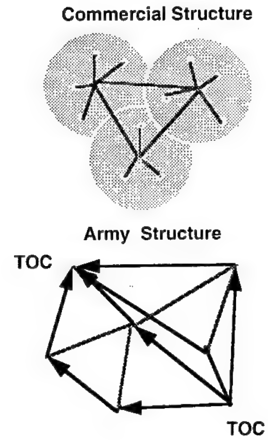
Message Routing Is More Complex in Army Networks — Dynamic Topology

Communications functional requirements

↓

Communications performance requirements

Commercial and Army rqmts	Army unique
• timeliness	• prioritization
• throughput	• self-organization
• efficiency	



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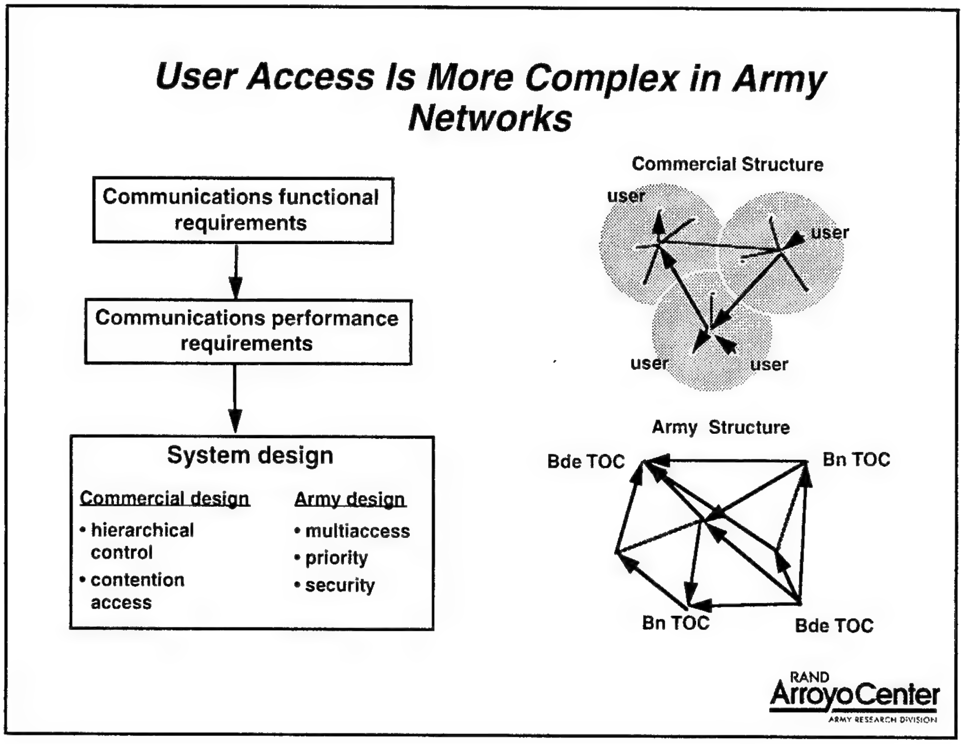
Routing through the networks also differs.

Commercial system designers focus on performance requirements for efficient service: increasing timeliness, throughput, and efficiency of bandwidth. Routing structures minimize multiple routes to take advantage of the most efficient (shortest, based on current network usage) routing structure. In current cellular telephone networks, circuit switching within the fixed network structure is most efficient. In the future, new switching algorithms such as Asynchronous Transfer Mode (ATM) can provide efficient service without tying up circuits. ATM for commercial users, though, will still require a fixed infrastructure network.

Army users will typically stretch communications network capacity. Users and routers will also be moving, continually changing the network topology. Army requirements are for efficient usage while using a network structure that is continually changing. To meet operational requirements, then, Army networks must be able to prioritize users and message traffic and to self-organize. (Self-organization is necessary because of the continually changing communications topology as units and vehicles move.) In this case, the Army will need to develop new protocols supporting dynamic network topologies.



Finally, the differing physical structure and routing schemes between commercial and Army communications networks impose different overall system designs, especially in network control and access.

Commercial systems are able to use a hierarchical control means using the fixed station infrastructure. Users access the system on a contention basis. Service basically treats each user as an individual.

Army requirements for prioritization and self-organization, combined with the physical structure of the network, result in the need for dynamic network control focused on decentralized network control to support the integrated user population.

New Commercial Satellites Can Meet Some Army Operational Needs

- **Commercial communications satellite systems**
  - **Provide global service with varying infrastructure**
    - **some with fixed ground stations**
    - **some support mobile user handsets**
  - **Use packet or circuit switching**
- **Army operational requirements for deployability, dispersion, connectivity could be met by commercial systems**
  - **But needs for mobility (users and infrastructure), security, multimedia will not be met**

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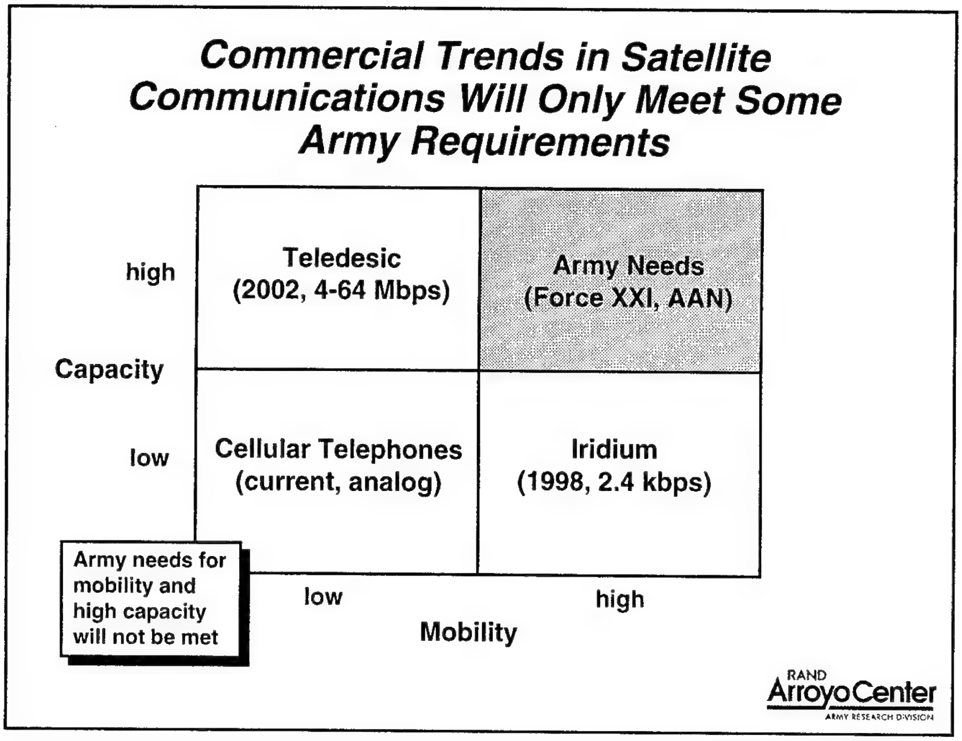
Commercial users have some requirements for independence from a communications infrastructure. Commercial communications companies are developing a number of new network systems, based on low Earth orbiting satellites, to provide global service. These have varying dependence on a fixed infrastructure:

- Some still use fixed ground stations, using the satellite links to eliminate the need for land-line wiring (still using circuit switching).
- Some have completely mobile stations, so that users with a handset link directly to a satellite network which then routes either to another mobile user or to an existing public service provider (routing using packet switching).

Army operational requirements are simultaneously increasing, as Force XXI and Army After Next call for increased information sharing across all echelons and functional areas. Commercial systems could meet some of the Army's future requirements, such as for deployability and connectivity. However, there will remain other needs that will not be met, for instance mobility, multimedia, and security.

The next chart amplifies unmet Army needs by looking at the simultaneous needs for mobility and high capacity (to support multimedia communications).



New commercial systems based on using satellites in low Earth orbit (800 to 1500 km orbits) will greatly increase mobility and deployability. Users of these systems will connect with satellites orbiting in constellations, continually searching for the "best" one (typically the satellite with the best field of view to the user) and switching satellites as they move in their orbits. The satellites orbit in constellations, and they switch messages among themselves to find the addressee (either another mobile user or a public switched network). Routing in these systems typically uses packet switching, but for a changing yet predictable network topology.

These systems promise to satisfy many Army requirements but still fail to meet needs for high mobility and capacity, as shown on this chart. There are two major commercial system types, as shown on the chart and represented by two typical commercial systems (Iridium and Teledesic).

Iridium is a Motorola system that uses a satellite constellation to link mobile users with handsets similar to current cellular telephones. Service is mostly for voice and data, over fairly low-capacity links of 2.4 kbps. Iridium expects to begin service in 1998.

Teledesic provides a much higher capacity network, with "fiber optic quality" (99.9 percent or higher connectivity). The Teledesic system can provide from 4–64 Mbps, but through stationary ground stations. Teledesic expects service to begin in 2002.

Outline

- **Communications system design framework**
- **Design process**
- **Design tradeoffs**
  - **Commercial wireless technology**
- **System level modeling issues**
- **Concluding remarks**

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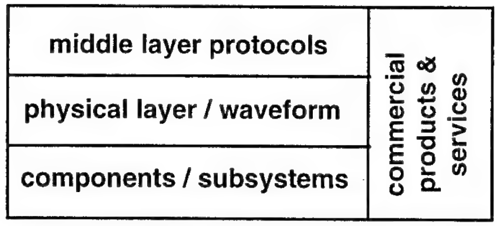
The next section presents assessments of specific commercial wireless technologies in terms of how well they meet Army requirements.

Commercial Wireless Technology: Four Levels of Capabilities



Assessment process:

1. How does commercial wireless technology meet Army requirements?
2. Are commercial technologies feasible solutions considering business practices and external environment?
3. What are usable commercial technologies and unmet Army needs?

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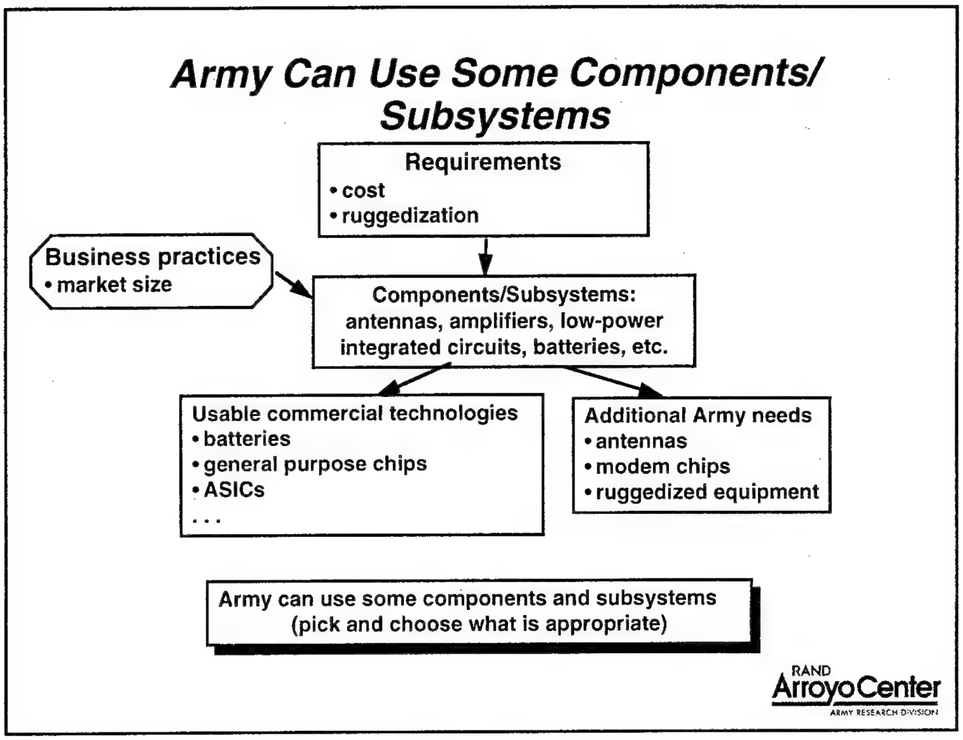
We categorize communications systems into four basic types:

1. Components/subsystems. These are the individual components and subsystems that might be used to construct a communications network, including any hardware not usable except when integrated with other components and systems to make a complete system.
2. Physical layer/waveforms. These are the waveforms used to establish links within a communications network, including modulation and error control techniques, spread spectrum, etc.
3. Middle layer protocols. These are the protocols used to route messages and control networks. They refer to Open System Interconnect (OSI) levels two, three, and four.
4. Commercial products. These are the complete commercial products that could be used or leased by the Army to provide immediate use.

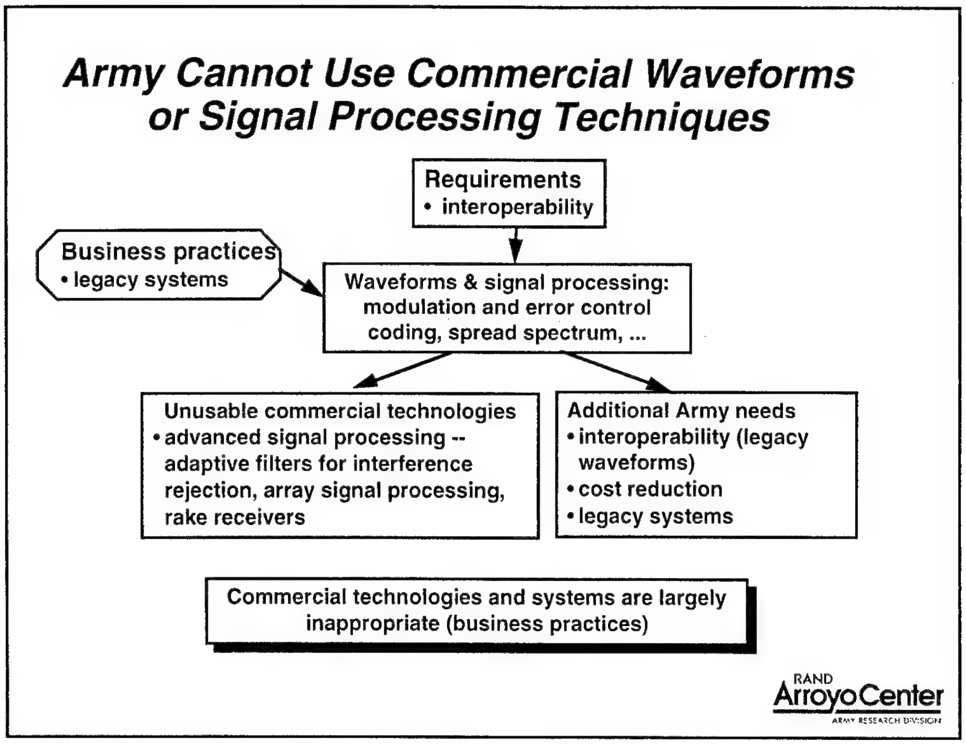
In order to assess the use of these systems for the Army, we use three criteria as listed on the chart.



A consequence of the DoD's mandate dispensing with most military specifications and standards has been a sharp increase in military contractors' use of commercial components. Because of the larger production volumes for commercial components, as well as competition among manufacturers and suppliers, costs do tend to be lower. For the most part, commercial components have also proved to be reliable for military use. In fact, because of large-scale production, commercial components are often more reliable and exhibit less unit-to-unit variation than comparable MILSPEC components. Thus, for many types of components there is no clear need for military-specific components.

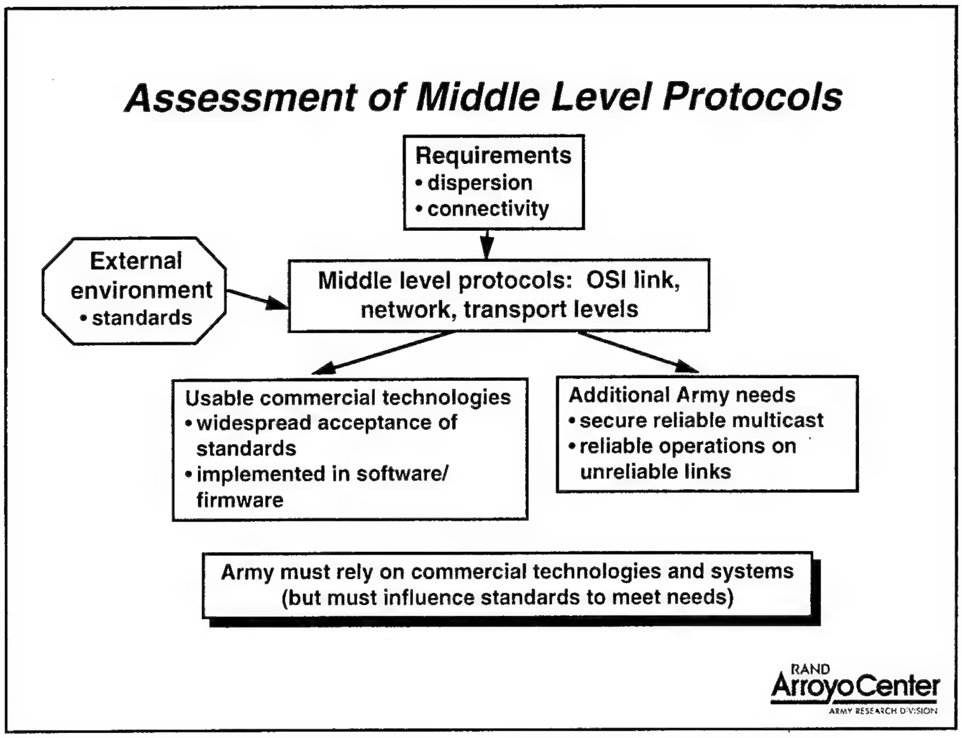
In some areas, however, military-specific components will continue to be necessary, and military funding may be necessary to ensure a reasonable pool of suppliers. Two component technology areas where some form of subsidy or other incentive research and development may be advisable are: (1) broadband high-power amplifiers (e.g., at X-band and above); and (2) high-gain low-sidelobe antennas and other antennas with unusual characteristics for specialized operations.

In summary, then, commercial products and technology trends can probably meet many of the military's needs in hardware/components. However, there will remain a number of specialized areas that will need military funding, especially as the military market shrinks relative to the commercial market.



A variety of signal processing techniques will be increasingly important for military wireless networks. These include digital demodulation, jammer side information processing, adaptive filtering for interference rejection, adaptive equalization, array signal processing, and multiuser detection. Some of these techniques require processing power that is not yet practicable for handheld or other small terminals. The military also uses much equipment that is old. Performance of the hardware and algorithms for these systems may severely limit the rates at which information can be transmitted, requiring a tradeoff between link quality/robustness and user data rate.

At this time, these limiting factors prevent the Army from taking full advantage of advanced signal processing, forcing a reliance on older and lower-performing techniques.



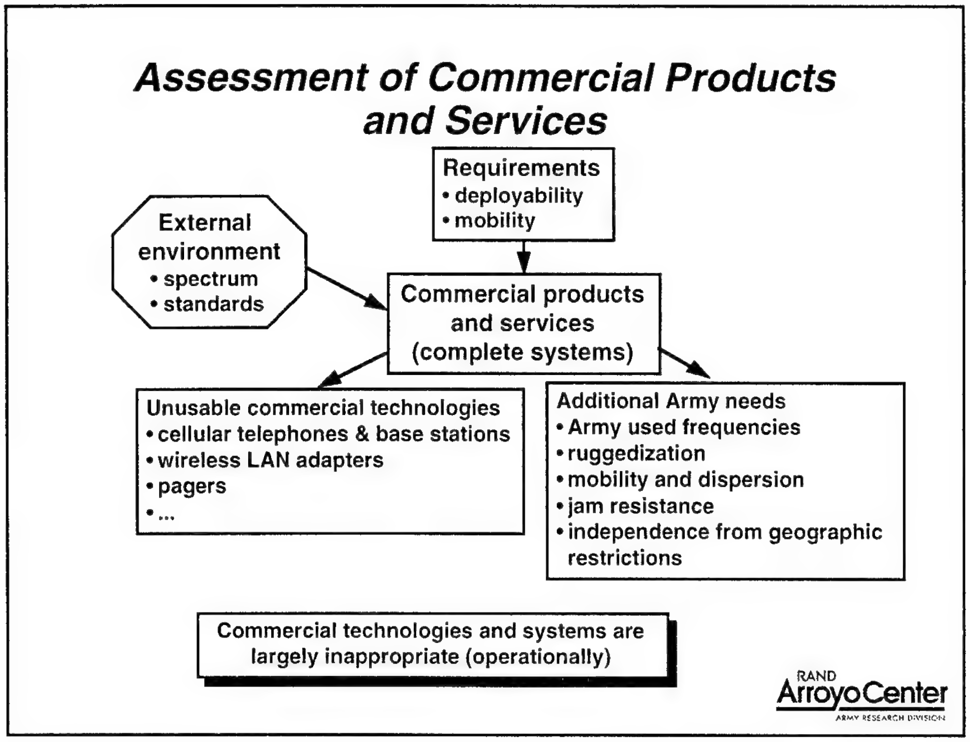
The middle layer protocols are OSI link, network, and transport layers (layers two to four). These are typically implemented using a combination of software and firmware, although some link layer functions are implemented directly in hardware. Layers three and four include the TCP/IP Internet protocol suite. The easiest way to achieve compatibility is by using the same layer three and four protocols in mobile wireless networks, but this may not be possible:

1. Mobile IP is a proposed addition to IP version 4 that would address some mobility issues until version 6 is ratified and widely available. Mobile IP and version 6 enable a limited type of mobility in which mobile hosts are permitted, but not mobile routers. Core functions such as routing will still be performed in the fixed, wired part of the network.

2. IP mobility is being implemented in a fashion transparent to applications, which has negative consequences. For instance, multimedia applications will not be able to dynamically reduce bandwidth to maintain real-time connections, and traffic cannot be dynamically resized to accommodate network data links with different link capacities. Both of these issues are important for Army networks, which are passing large amounts of multimedia data through heterogeneous networks.

3. Security issues, e.g., secure reliable multicast for groups with dynamic membership, will not be supported.

We feel, then, that current and planned standards for middle layers will not meet Army needs, and the Army needs to remain engaged in the standards process to ensure interoperability with diverse networks.



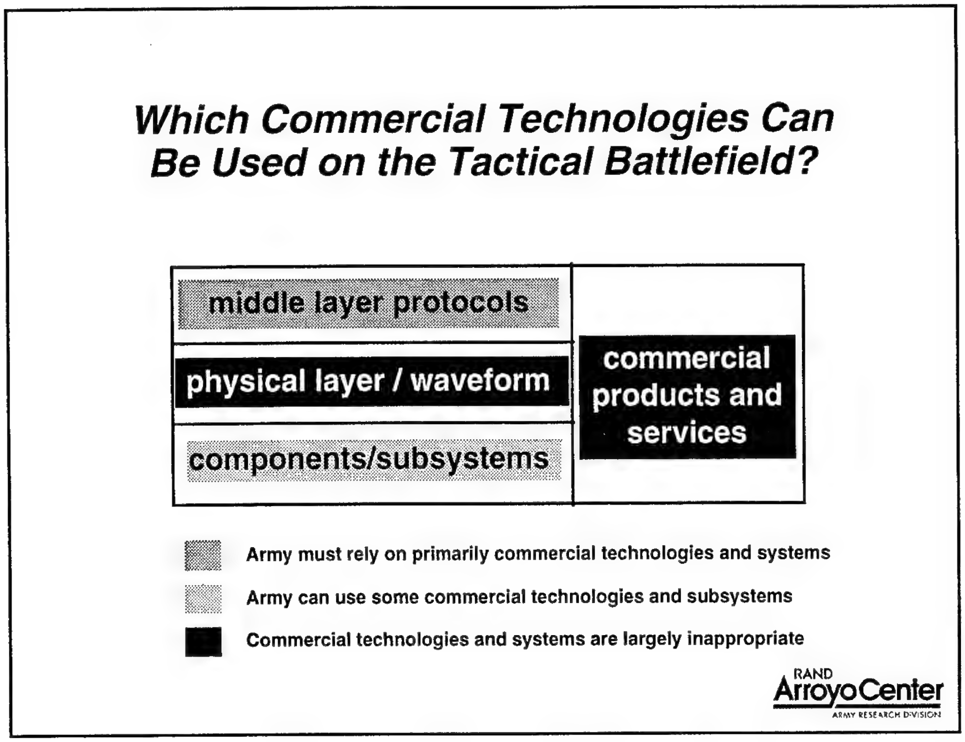
The commercial products category refers to the use of integral commercial communications systems by the Army. For a variety of reasons, including user familiarity in peacetime use, many users feel that commercial products can be used at lower cost than developing military systems. The Army could lease or contract to use systems and/or spectrum in areas where it operates, such as Western Europe, or could operate, such as Southwest Asia. Certainly these prearrangements would exist, facilitating the setup and use of communications networks.

But if the Army plans to be able to operate anywhere in the world, not necessarily with preplanning, then commercial systems have a number of drawbacks that preclude their use for our application (wireless communications on the tactical battlefield).

1. Commercial systems are still unavailable in many areas where the Army might need to operate.
2. Commercial systems depend on wired infrastructure that is vulnerable (commercial satellite systems will not meet capacity and mobility needs of the Army, as previously discussed).
3. Army users would need to compete with other public users, who may have legal rights to usage. (Commercial systems would not necessarily be owned and operated by U.S. companies.)

4. Different standards exist for different areas of the world, so the Army would need to keep a substantial inventory to meet every contingency.

Our summary, then, is that commercial cellular products are mostly not useful except for specialized operations (e.g., where low capacity is needed, or for peacekeeping operations).



This chart summarizes our assessment of the utility of commercial wireless technologies to meet Army needs. It is important that many of our assessments are based not only on how well systems meet Army requirements, but just as importantly are based on how external constraints (business practices, external environment) affect system design.

It is important to note that none of these areas will support Army reliance on primarily commercial technologies and systems.

Outline

- Communications system design framework
- Design tradeoffs
- Commercial wireless technology
- System level modeling issues
- Concluding remarks

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The next section discusses some system level modeling issues.

Tools for Making System Design Tradeoffs

- **Performance assessments typically use models to simulate performance**
- **Most urgent need for modeling to aid analysis is at system level, especially for communications channels**
  - **Army has encountered problems with SINCGARS modeling—estimating interference for varying user densities**
  - **Commercial world has encountered problems assessing performance of CDMA systems**
- **Channel models are needed to**
  - **Simulate large-scale network performance**
  - **Provide common reference for system comparisons**

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Modeling and simulation are used by system designers to help make tradeoffs. They are especially useful when specific performance tradeoffs are needed for detailed design of architectures and network structures.

Both the commercial world and the Army have encountered problems in fielding commercial systems designed with current system level models and simulations. The Army, for instance, has used models and simulations to design the network structure for the Tactical Internet for Task Force XXI. (And redesign in the field was necessary when the models proved inadequate.) The Army has also had problems with SINCGARS in estimating interference as user density changes. The commercial world has also recently encountered problems when implementing code division multiple access (CDMA) coding in cellular networks.

These problems can be traced to a lack of realistic channel models. Channel models simulate realistic propagation conditions for wireless communications (line of sight, multipath, wavefront propagation) within a network. This is especially important for packet switching. Realistic channel models provide a tool for estimating scaling problems in networks, and they also provide a common reference for comparing performance of competing systems.

Outline

- Communications system design framework
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The last section of the report consists of concluding remarks.

System Design Requires Tradeoffs

- Commercial wireless technologies will largely not meet Army tactical needs
  - Requirements differ
  - Army design choices are subject to external constraints
- Army can pick and choose the right pieces of commercial network technologies
  - and, fund research to fill the missing pieces
  - and, relax constraints by engaging in standards working groups, reducing dependence on legacy systems
  - or, reassess requirements
- Commercial systems can often be adapted, but changes tend to increase costs sharply
- Requirements need to be tied to system tradeoffs—decisions at each step of design process affects capabilities
  - We provide such a framework in this study

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This chart reiterates the basic theme of the study, that system design requires tradeoffs. Commercial wireless systems will not meet the Army's future needs, and the Army needs to trade off requirements with future investments in research and Army-unique systems.

Tradeoffs are complicated because:

1. Tradeoffs at one level of the design process affect the choices at other levels.
2. Tradeoffs are not necessarily driven by requirements, but also by external constraints of business practices and the external environment.

We provide in this study a framework for system design that links requirements to decisions in the design process.

Recommended Areas for Research Emphasis

- Components and subsystems
  - broad-band devices and amplifiers
  - adaptive notch filters
  - passive radiometers for ground terminals
- Signal processing
  - bandwidth-efficient modulation and coding
  - multiuser detection for CDMA
  - combining signals from multiple receivers
- Network protocols
  - reliable routing on multihop wireless networks (reliable UDP)
  - protocols for combined line-of-sight and relayed comms
  - routing and queuing algorithms for precedence and perishability
- Channel and interference modeling
  - continuous channel models
  - statistical modeling of interference
  - predicting mutual interference via simulation

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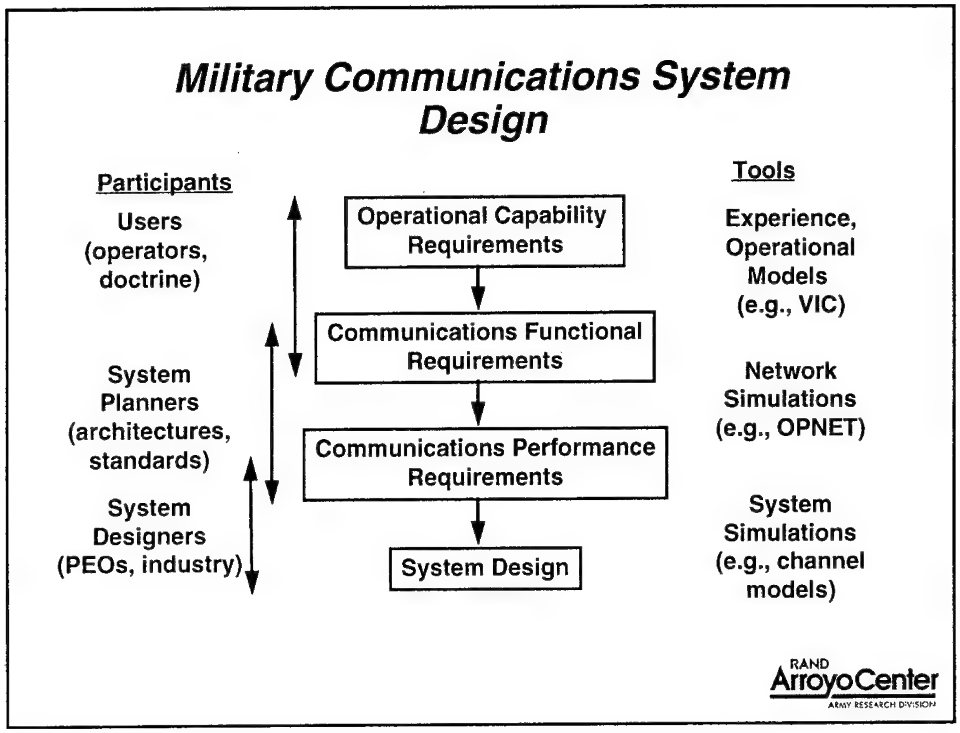
This chart gives some of the more detailed recommendations for future research.

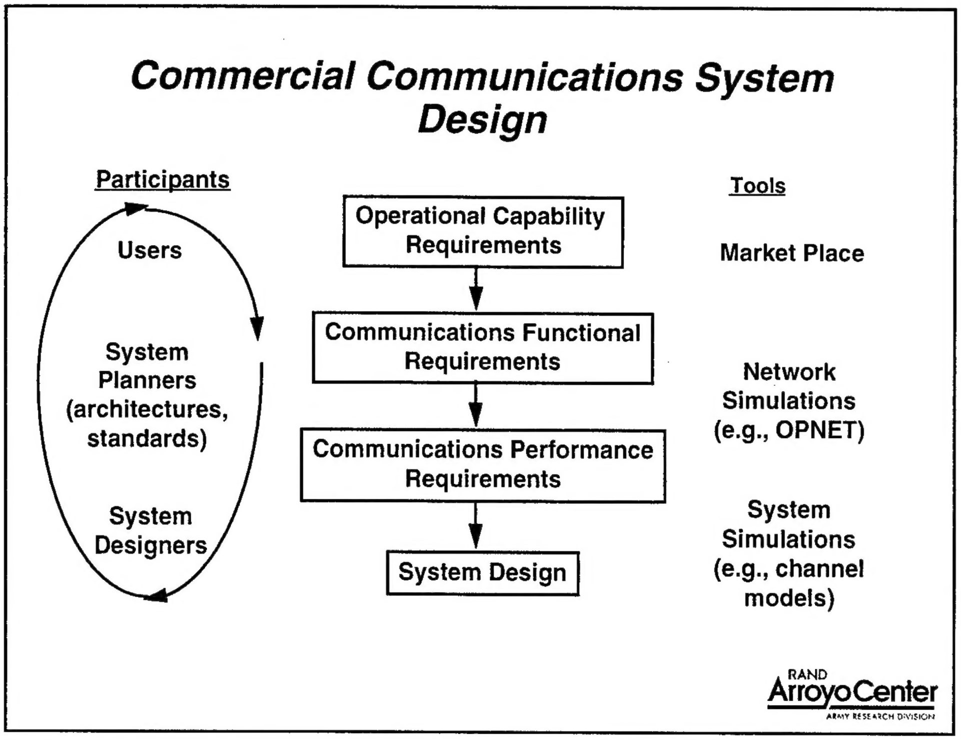
Back-ups

This section provides some backup material for the briefing.

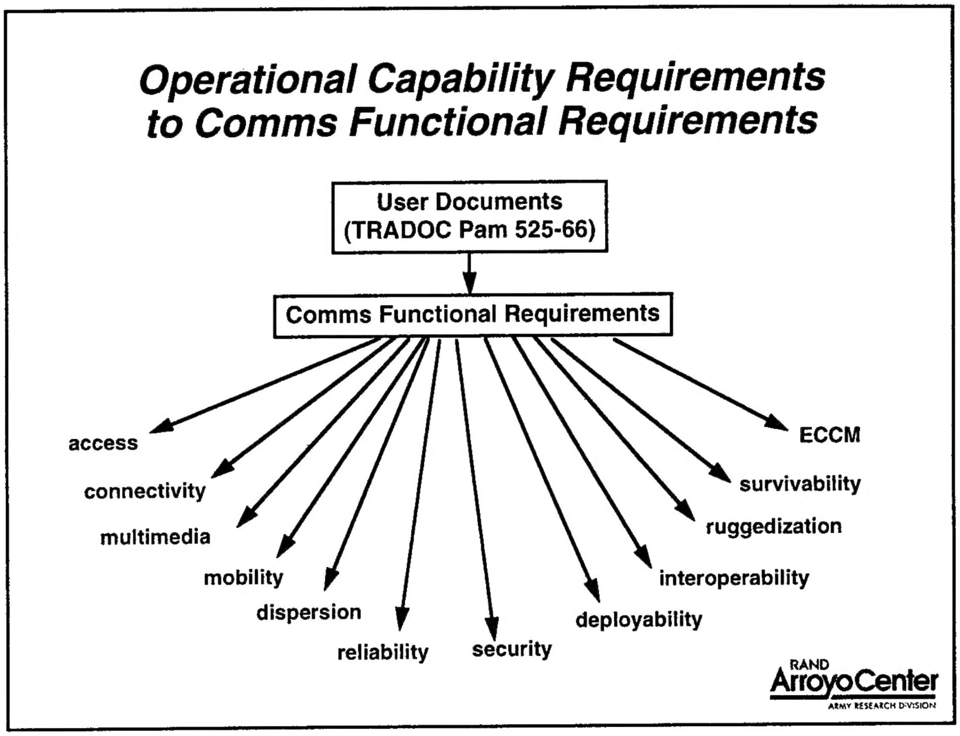


This chart shows a fuller system design tradeoff process for the military. On the left-hand side, the chart shows that different agencies and designers become involved as the process moves from requirements to system design. It is especially important in this process to track decisions and tradeoffs at each level, as not only do decisions impact other levels, they could be performed by other organizations. An explicit linkage is then necessary to make sure the system fits together.

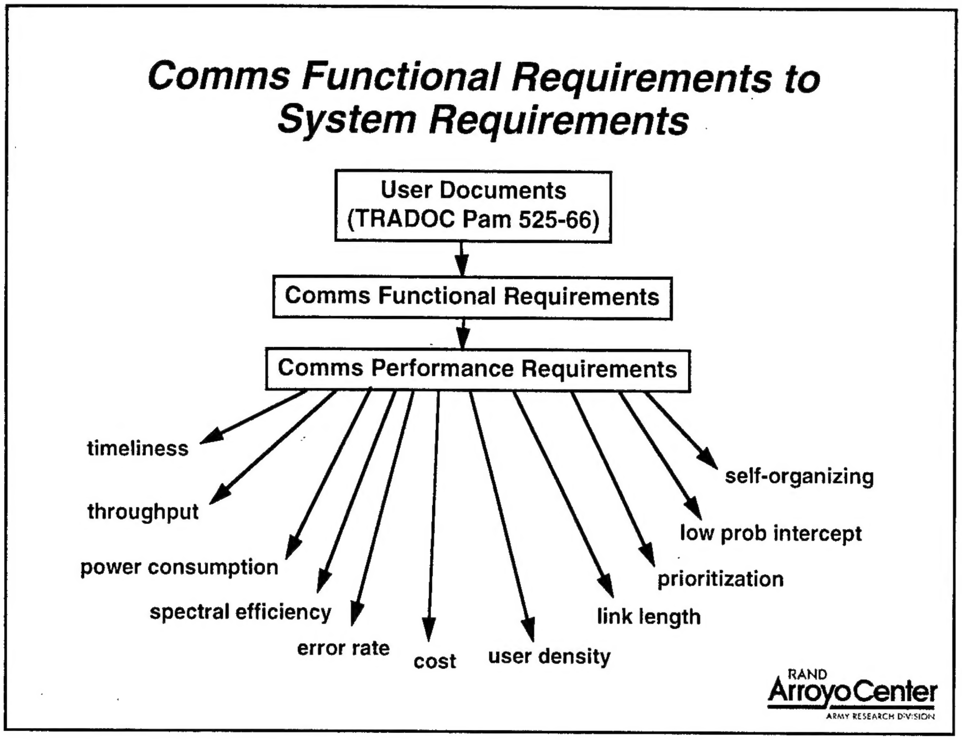
The right-hand side of the chart shows some of the analytic tools used in the design process, from operational models to network simulations to system simulations.



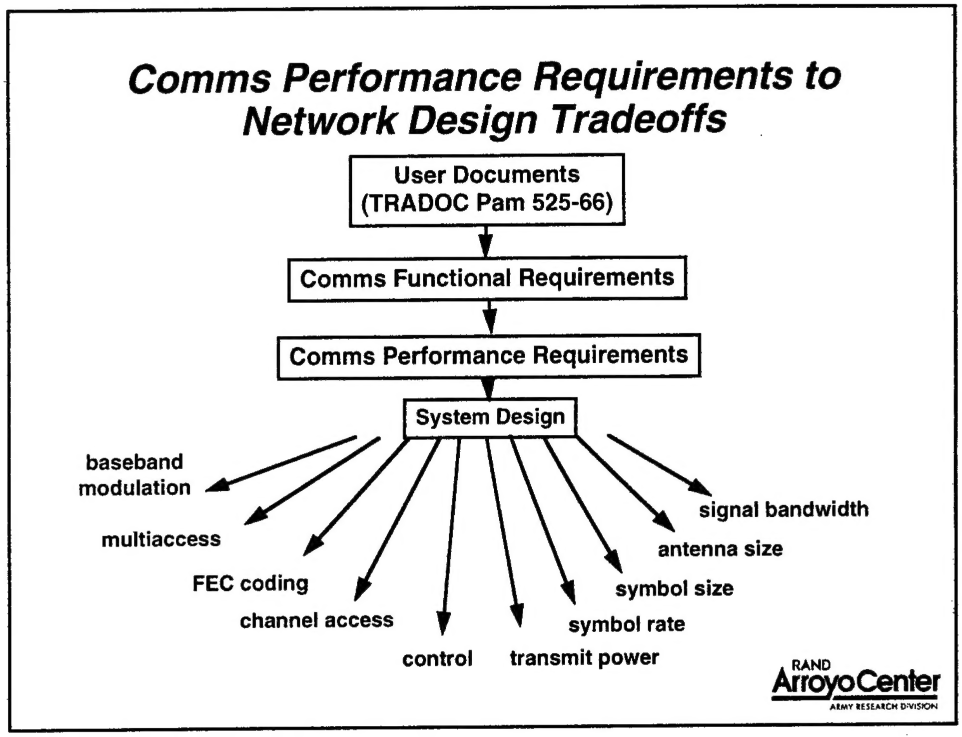
This chart shows how the commercial world develops communications systems. In this case, participants in the design process are frequently part of a larger design team, with a prime contractor maintaining configuration control.



This chart details the measures and categories of communications functional requirements. Choices among these parameters should reflect the operational requirements as defined by the user. In our study, we examined the Operational Capabilities Requirements in TRADOC Pamphlet 525-66.



This chart shows the design parameters at the communications performance level. This level uses parameters that might not be translatable to the user, but reflect the requirements of communications system designers.



This chart lists the detailed system design choices that must be made by the system builder.